1. Science aim/goal:
Determine the range and typical value of the ice/rock ratio in protoplanetary and debris disks across the stellar mass range and at all evolutionary stages.

2. (i) Scientific Importance:
Water is a key ingredient for habitable planets. In protoplanetary disks, ice initially begins as pristine before it is incorporated into 'wet' planetesimals to form comets and the cores of Jovian planets. Terrestrial planets may form wet or receive water from comets or asteroids during the debris disk stage (Fig. 1A).

Is our solar system a typical outcome of these processes? Directly measuring the abundance of ice in protoplanetary and debris disks, via the ice/rock ratio, is essential to answer this. Beyond the thermal desorption snowline, ice abundances may vary due to the effects of dust settling, photo-desorption, and chemical reactions. These processes depend on stellar properties that evolve with time.

Most of the mass that will be incorporated into planetesimals is found in the disk midplane. Only two spectral features of ice can probe this region: a pristine ice feature at 47μm and two processed ice features at 43 and 62μm (Fig. 1B). The 62μm ice feature has been detected in a handful of bright, flared disks with *Herschel* PACS (McClure et al. 2012, 2015); however it has a low peak/continuum ratio and went undetected in the majority of disks. The much stronger 43μm feature was detected in disks by *ISO* LWS (Malfait et al. 1998, 1999; Min et al. 2016). Neither *Spitzer* nor *Herschel* covered this feature, which is an excellent proxy for the ice/dust mass ratio. *Measuring the bulk ice mass and degree of thermal processing through these features is critical to quantify the potential for habitability of protoplanets.*

(ii) Measurements Required:
To advance this science goal, we must make a census of the 43μm feature in a large sample (~1000 targets) covering a range of stellar masses and degrees of disk evolution, from gas-rich disks to the debris disks that are analogs to our solar system at the time of cometary ice delivery to terrestrial planets. Low spectral resolution (R~250 at 43μm) is sufficient to separate the features from the continuum; the driver is high continuum sensitivity at distances to 500pc in order to distinguish ice/rock ratios down to 0.13 (~1/10th solar). The angular resolution requirement (0.5"; Table 1) will allow us to associate variations in the abundance with radial structures common to these systems (proto-Kuiper belts, disk gaps, spiral arms), for a subsample of the ~50 largest and closest protoplanetary and debris disks.

(iii) Uniqueness to 10μm to few mm wavelength facility:
The 43-47 and 62μm features trace ice at temperatures of 50-150K in direct emission. Typical disks are also optically thin down to their midplanes in the far-IR, so these are the only spectral features capable of probing the bulk mass of ice near the disk midplane.

(iv) Longevity/Durability:
Water ice can be observed in light scattered from the disk atmosphere at 3μm with current ground based facilities and future JWST and EELT instruments; however those features do not probe the bulk ice mass. SOFIA HIRMES, if approved, will be able to

observe the 43μm feature with sufficient sensitivity for a much smaller sample of bright, nearby protoplanetary disks. There is no other facility that can access the wavelength regime required for this science goal.

3. Figure:

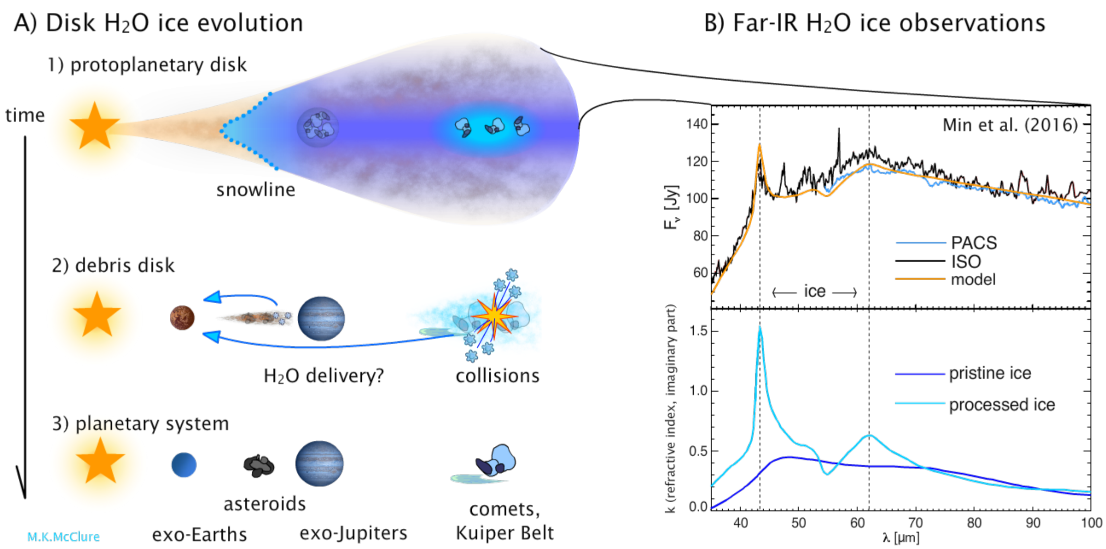

Figure 1, A: Schematic of ice evolution in disks, from pristine (ISM, dark blue) early on to processed (cyan) via planetesimal collisions, concurrent with formation of Jovian and terrestrial planets and delivery of water to the inner solar system. B: Example detection and fit of the 43 and 62μm features by Min et al. (2016).

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	30-60μm	30-100μm	Larger wavelength range covers weaker 62μm feature.
Number of targets		~1000	>1000	
Angular resolution	"	0.5@43μm	0.25	Required value resolves typical wide binaries at 43μm for 150pc. Desired value resolves Kuiper Belt within 160pc.
Spectral resolution	λ/Δλ	250@43μm	-	
Bandwidth	μm	20	30	
Continuum Sensitivity (1σ)	μJy	4	1	Calculations in appendix
Signal –to-noise		25	100	Calculations in appendix
Dynamic range		5e7	2e8	Calculations in appendix; driven by desire to observe a handful of bright nearby disks (200 Jy@60μm); higher spatial resolution or exclusion of these targets could reduce required range
Field of Regard		Galactic plane +/-20°		

5. Key references: Boogert et al. (2015, ARAA, 53, 541); Pontoppidan et al. (2014, PPVI, 362); van Dishoeck et al. (2014, PPVI, 835)

Appendix: Sensitivity estimates:

S/N: If we require 5σ detections of ice/rock ratios of 1/10th of the solar value (~0.13) in the lower end of the range of 'typical' M0 star disks (ε=0.001, peak/continuum ratio = 1.2) at the mean distance of Orion (500pc), then we need ***S/N=25*** on the continuum. The 'typical' disk means one with dust settling in the range of ε=0.001-0.01, based on observations of disks in Taurus by Furlan et al. (2006).

If we desire 5σ detections of ice/rock ratios of 1/10th of the solar value (~0.13) in the most evolved M0 star disks (ε=0.0001, peak/continuum ratio = 1.05) at the mean distance of Orion (500pc), then we want ***S/N=100*** on the continuum. We note that this S/N is better for extending the low- and high-mass stellar sample to 1kpc to reach our desired number of targets.

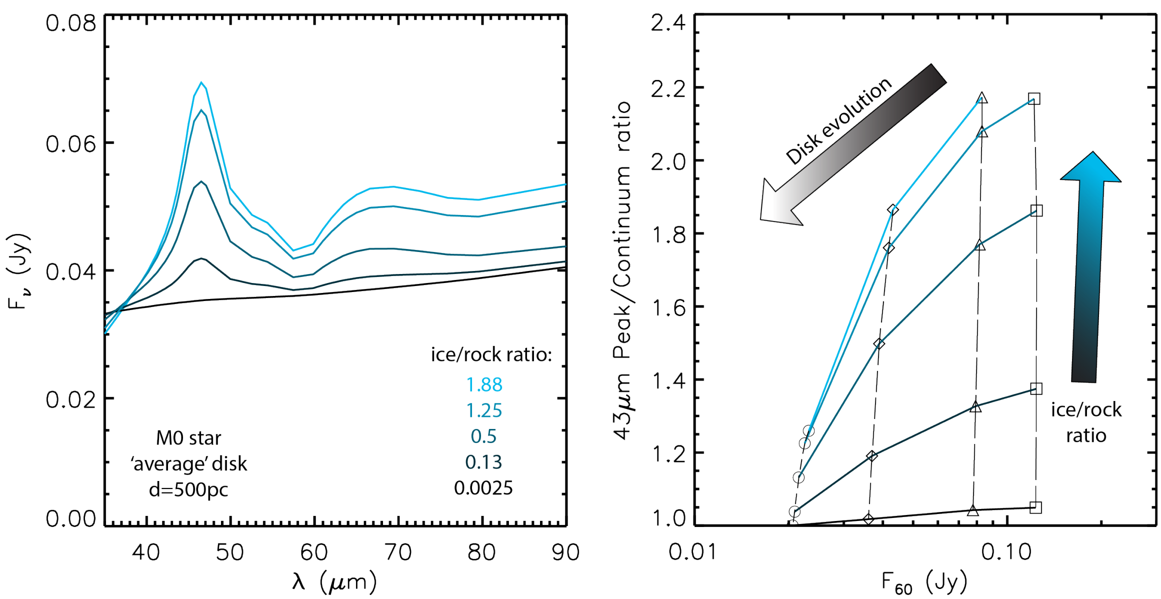

Figure 2: (left) Model spectra (D'Alessio et al. 2006, McClure et al. 2015) of far-IR processed (crystalline) ice features with varying ice/rock ratios, for a 'typical' disk around an M0 star at the distance of Orion. (right) Comparison of the peak/continuum ratio of the 43μm feature vs. 60μm continuum flux for the same disk with different degrees of dust settling to the disk midplane (a proxy for disk evolution). Settling is indicated by the vertical, dashed lines with *ε=0.0001, 0.001, 0.01, 0.1 (from left to right).*

Continuum sensitivity and dynamic range: At the distance of Orion (500pc, necessary for disk sample ~1000), an M9 brown dwarf disk, depending on its dust distribution and temperature structure, is between 0.1mJy and 1mJy in continuum flux at 60μm. Combined with the S/N requirement, this sets the lower limit on our continuum sensitivity to ***4μJy required, 1μJy requested***. This allows detection of the most evolved disks around low-mass stars at the distance of 1kpc as well. Disks of nearby A stars set the upper limit for our range, ~200 Jy, for a total dynamic range of $\boldsymbol{2x10^8}$.

Numbers:

From c2d (Evans et al. 2009), IRS_Disks (Furlan et al. 2009), there are 789 protoplanetary disks in Cha I, Cha II, Lupus, Perseus, Serpens, Ophiuchus, and Taurus-Aurigae. This doesn't count disks in the Orion association clouds, or the ~570+ debris disks observed by *Spitzer*'s InfraRed Spectrograph (Chen et al. 2014). Achieving a sample of **1000 disks** is very reasonable; in all likelihood **hundreds more** can be observed with the proposed specifications.